UCRL-TR-204971

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POGAL B-Axis Motor Test

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June 29, 2004

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This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

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January 15, 2003

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Introduction

The Aerotech model S-180-69-A, a brushless DC motor of slotless design, was selected as the B-axis drive for the Precision Optical Grinder and Lathe (POGAL). It is common knowledge that a slotless motor will have effectively no magnetic cogging and much less torque ripple than a traditional slot-type motor. It is logical to believe that the radial and axial forces generated between the rotor and stator would also be smaller for a slotless design. This is important when a frameless motor is directly coupled to the axis, as these forces directly influence the axis and affect its error motion. It is the purpose of this test to determine the radial and axial forces generated by the Aerotech motor and to estimate their effect on the error motion of the axis using a mathematical model of the hydrostatic bearing being designed for POGAL.

The test results combined with a mathematical model of the POGAL B axis indicate that the directly coupled Aerotech motor will be quite acceptable. In the radial direction, the residual motor force, after subtracting out the one-cycle force, could cause sub nanometer level error motion at the tool point. The axial direction is not in a sensitive direction for turning.

Test Apparatus

Figure 1 shows the test stand set up for the Aerotech motor. The motor rotor mounts to an aluminum shaft that rotates on a Professional Instruments 4B Blockhead air-bearing spindle. The spindle housing attaches to a stationary structure formed by two, aluminum plates shown below and to the right. A parallel-link flexure stage supports the stator and is used to measure disturbance forces generated between the rotor and the stator. Also shown are two LVDTs that measure radial and axial displacement of the stator. Displacement is proportional to force for frequencies well below resonance. The radial LVDT is centered on the motor, orthogonal to the spindle axis. The axial LVDT is parallel to but off center from the axis to simplify the mechanical set up and to measure directly against the annular stator. The flexure stage has been calibrated to a force gauge.

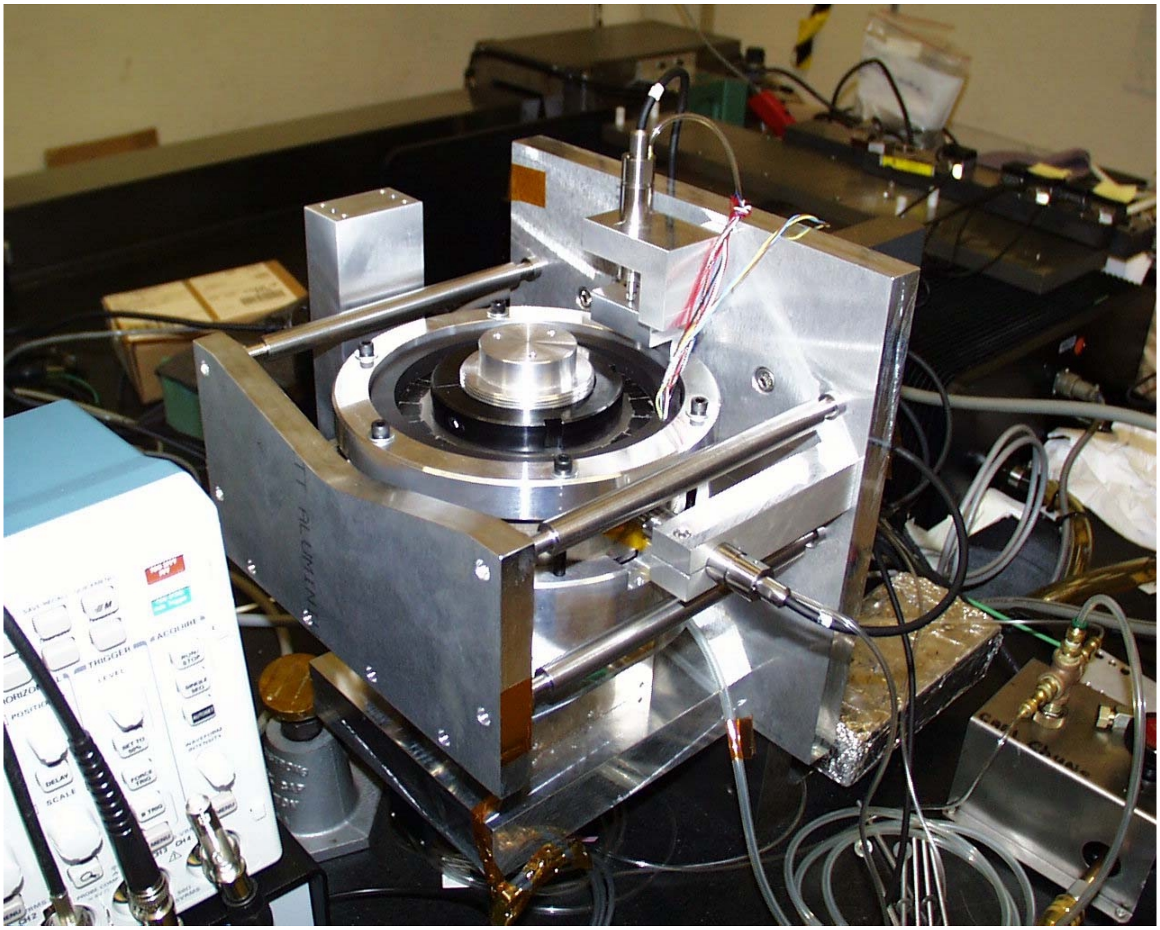

Figure 1 Photograph of the test stand.

An AEROTECH BAL 10-40 linear three-phase amplifier powers the motor. A brake can be set to operate the motor under load at relatively low speed. The rotation angle of the motor is measured with a Heidenhain ERA180 optical encoder with 9000 sinusoidal cycles per revolution. A Delta Tau PMAC controller commutates the motor, closes the velocity loop and records data from the instruments.

Test Results

Calibration for radial and axial force measurements

The flexure stage was calibrated for force by applying up to 8.0 lb through the center of the stator with a force gauge and measuring the displacement with the LVDT. Figure 2 shows straight-line fits to the data collected for axial and radial directions. The slopes are the calibration factors: 3478 lb/in for axial and 1925 lb/in for radial. The flexure stage by itself has approximately the same stiffness in both directions, but magnetic attraction between the rotor and stator acts as a negative radial stiffness that initially exceeded the flexure. A die spring was added in the radial direction to obtain a net positive stiffness. It is important to consider the consequences of the stator being mounted to a relatively flexible stage compared to the POGAL mount, which will be 10 to 100 times stiffer.

Suppose a radial force of one unit exists between the rotor and the stator on a rigid mount. The flexible mount would allow the stator to move closer to the rotor resulting in a larger force. Since the stator has been calibrated with the rotor in place, the larger force at the displaced location is calculated to be one unit force, which is the desired result.

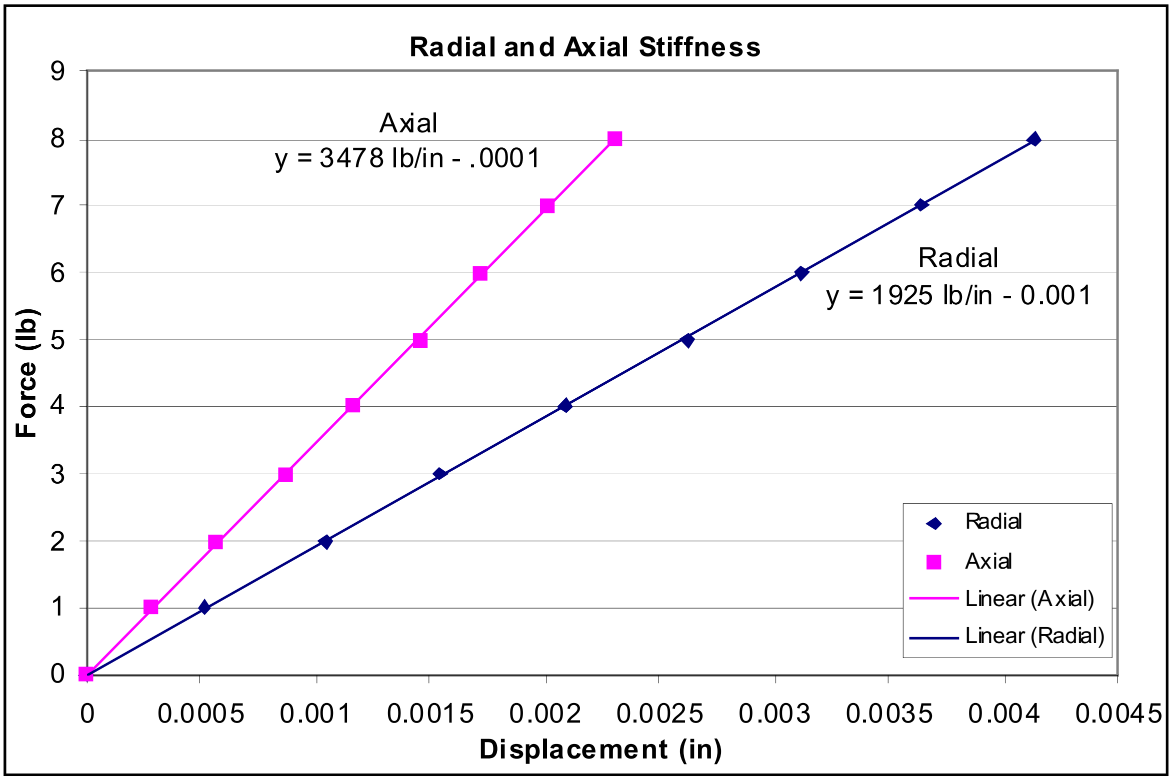

Figure 2 Radial and axial calibration plots for the flexure stage.

<u>Back EMF of motor phases</u>

Balance between the three phases of the motor is important to minimize torque ripple and presumably disturbance forces too. The back EMF voltage of each motor phase and the motor angle were sampled at equal time increments while rotating the motor by hand. Dividing the back EMF voltage by the calculated instantaneous velocity normalizes the measurement to a function only of angle. Ideally the function for each phase is sinusoidal with one cycle per pole pair or nine cycles per revolution for this motor. Further, all three phases should have equal amplitude and be equally spaced from one another. Figure 3 shows that the three measured functions compare very closely to ideal sinusoids. Applying standard sinusoidal commutation to this motor should give acceptably small variation in the voltage constant. Figure 4 shows the predicted variation, which overall is 3.2 % P-V. The average voltage constant is 2.61 V-s/r for (1, -0.5, -0.5) commutation and 3.01 V-s/r for (0.866, -0.866, 0) commutation. The torque constant is the same value expressed in units of N-m/A.

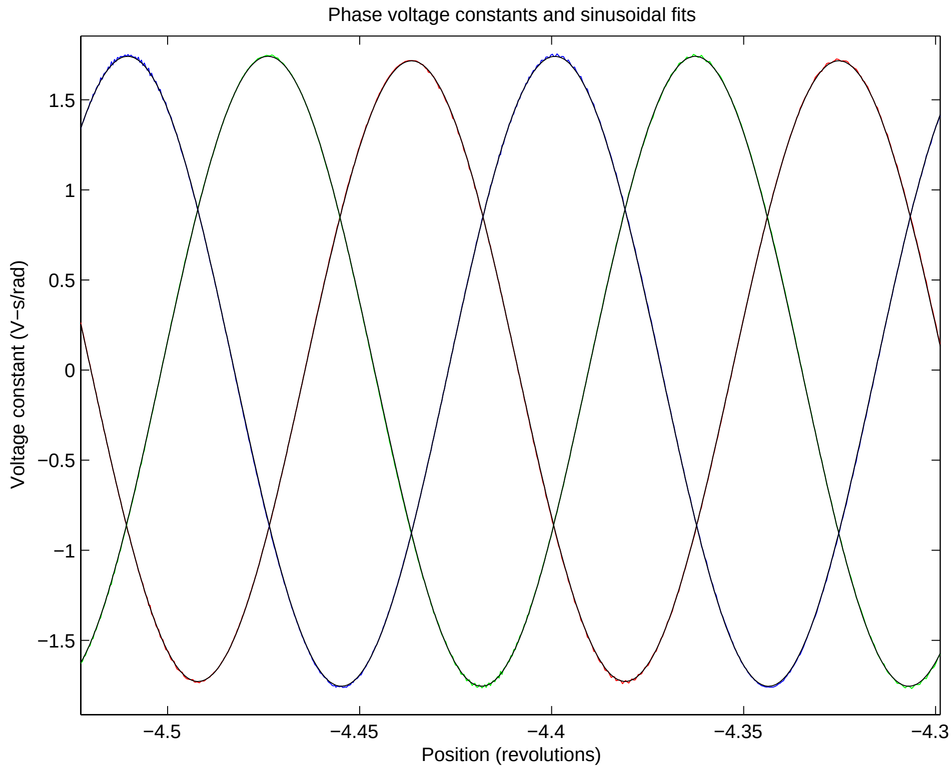

Figure 3 The voltage constant for each phase is very nearly a sinusoidal function of angle. Deviations between the measured (blue, green, red) functions and the ideal sinusoids can be seen near the peaks.

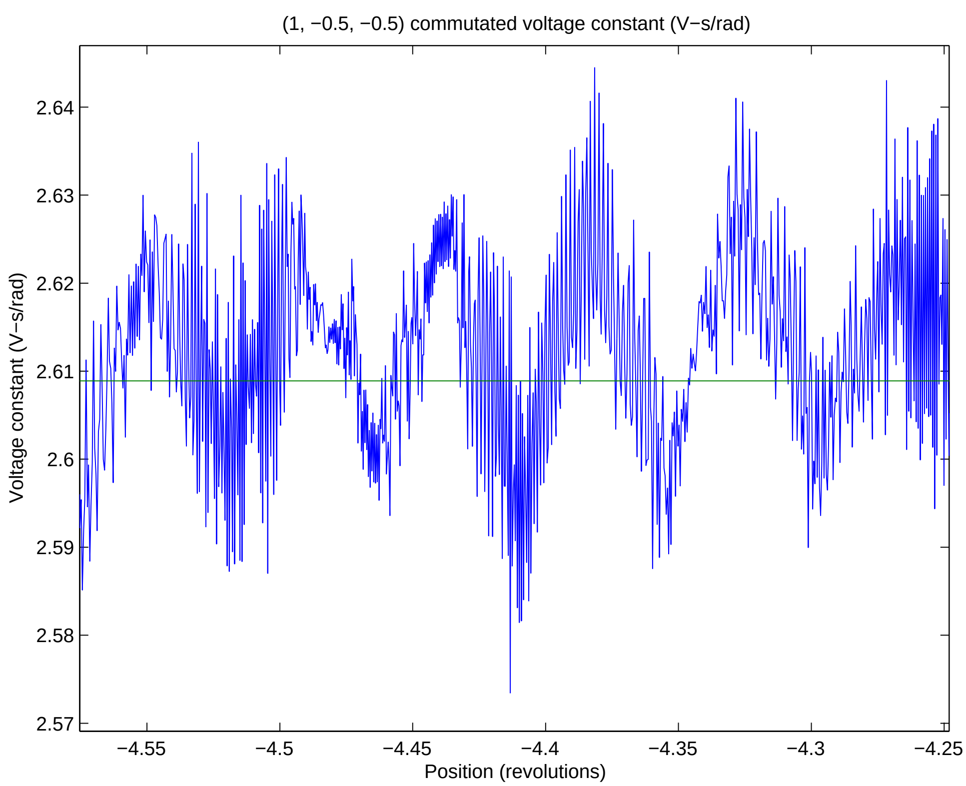

Figure 4 Computed using standard sinusoidal commutation, the voltage constant varies 3.2 % P-V.

Radial and axial disturbance forces

Radial and axial forces were computed from LVDT measurements using the calibration factors discussed previously. The motor could be operated under varying current levels by applying a friction brake to the spindle. The brake was designed to cause minimum influence in the radial and axial directions but the level of influence was not determined. The motor was tested up to 3 A peak or 83 % of its 3.6 A continuous current limit. Using the measured torque constant of the motor, the computed torque is 7.8 N-m. Normally the tool point would be on axis, but working off axis up to 100 mm or so is possible, where 3 A would generate 78 N (18 lb) of tool force. Thus the 3 A test conservatively represents a worse case finish operation where error motion is of up most concern.

Figure 5 shows the radial and axial forces for the no-load test of the motor, where the motor drives the spindle without the brake engaged. Both forces are largely sinusoidal with a period of one revolution. In the radial direction, the relatively large amplitude of 5.2 lb is caused by magnetic attraction between the 18 poles on the rotor and the annular laminations of the stator. The one-cycle radial force causes the rotational axis to shift slightly but this is a static condition. A one-cycle axial force is also present in the data but the magnitude is greater than expected for this motor configuration. There could be some cross coupling in the flexure stage, that is, radial force causing axial motion. If this exists, it would most likely show up 90° out of phase as observed in the data. This same behavior was observed when the spindle motor was tested on this same apparatus, thus making cross coupling the very likely explanation for both tests.

Figure 6 shows the forces for the 3 A test of the motor, where the motor drives the spindle against the brake. Note there is little apparent dependence on motor current. As Figure 7 shows, the one-cycle force is almost constant from 0.05 A to 3.0 A. Figure 8 shows that the residual amplitude, after subtracting the one-cycle force, has no obvious trend with current. Figure 9 compares the radial force occurring for the current extremes, 0.05 A and 3.0 A after having removed the one-cycle force.

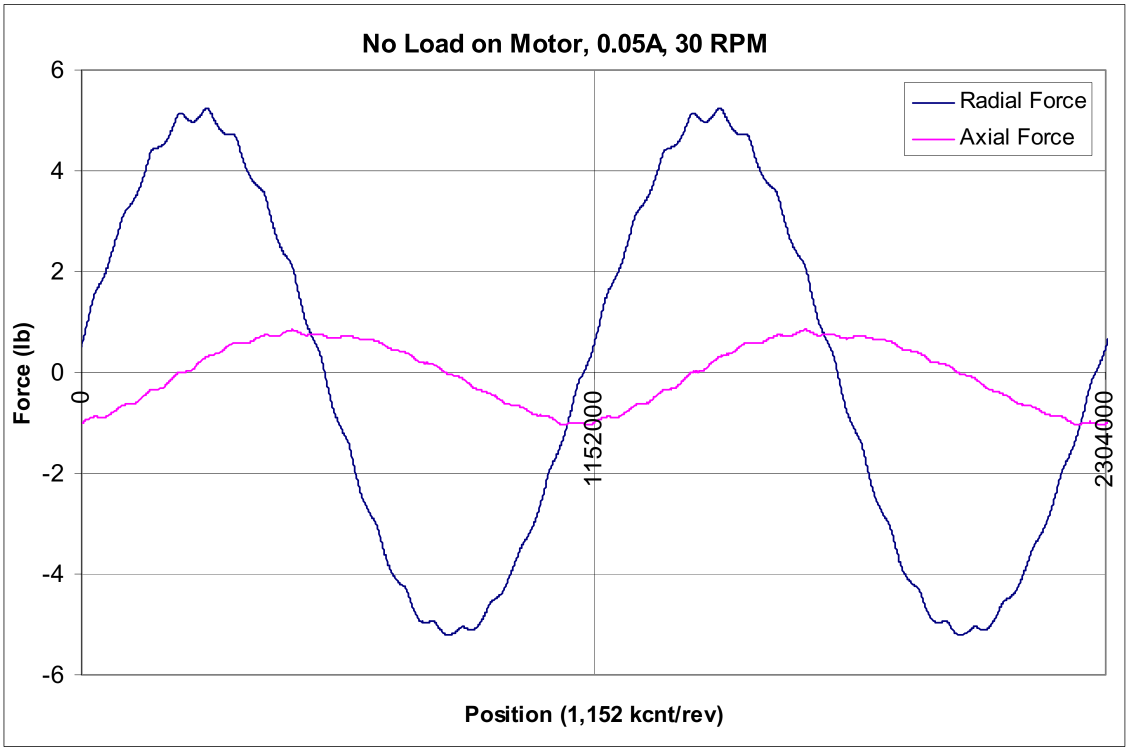

Figure 5 Measured radial and axial forces for minimum current.

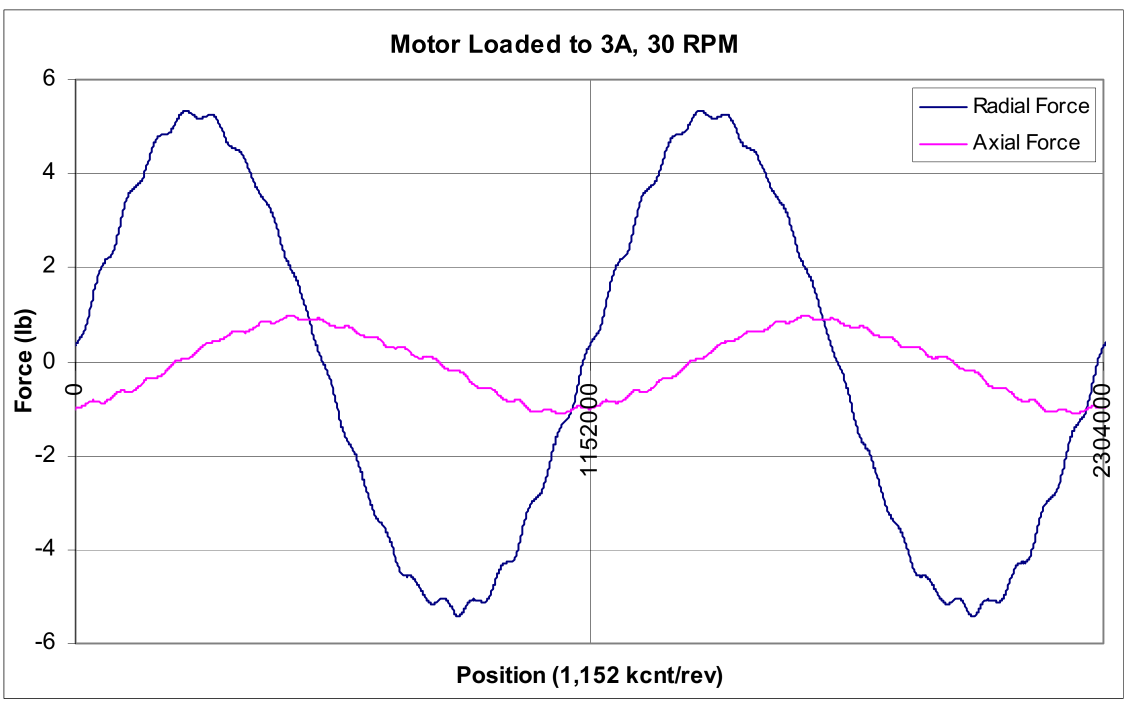

Figure 6 Measured radial and axial forces with the brake set to obtain 3 A peak current.

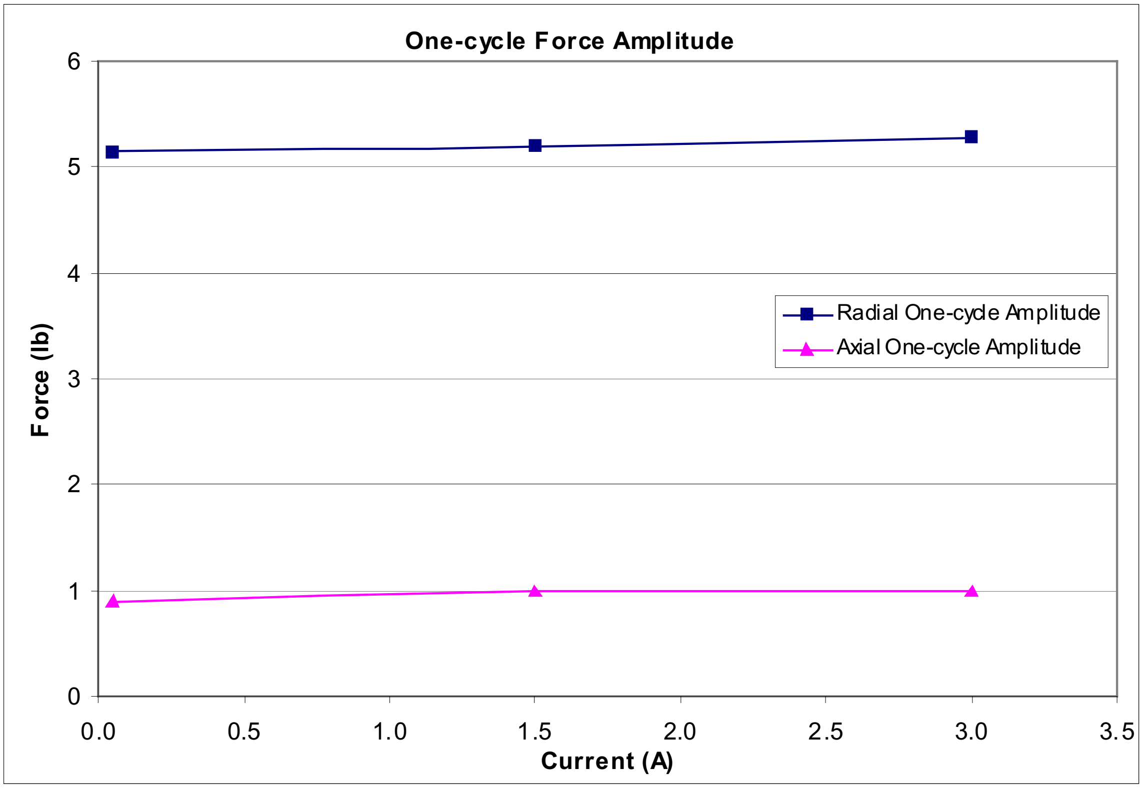

Figure 7 The one-cycle force amplitude is almost constant from 0.05 A to 3.0 A.

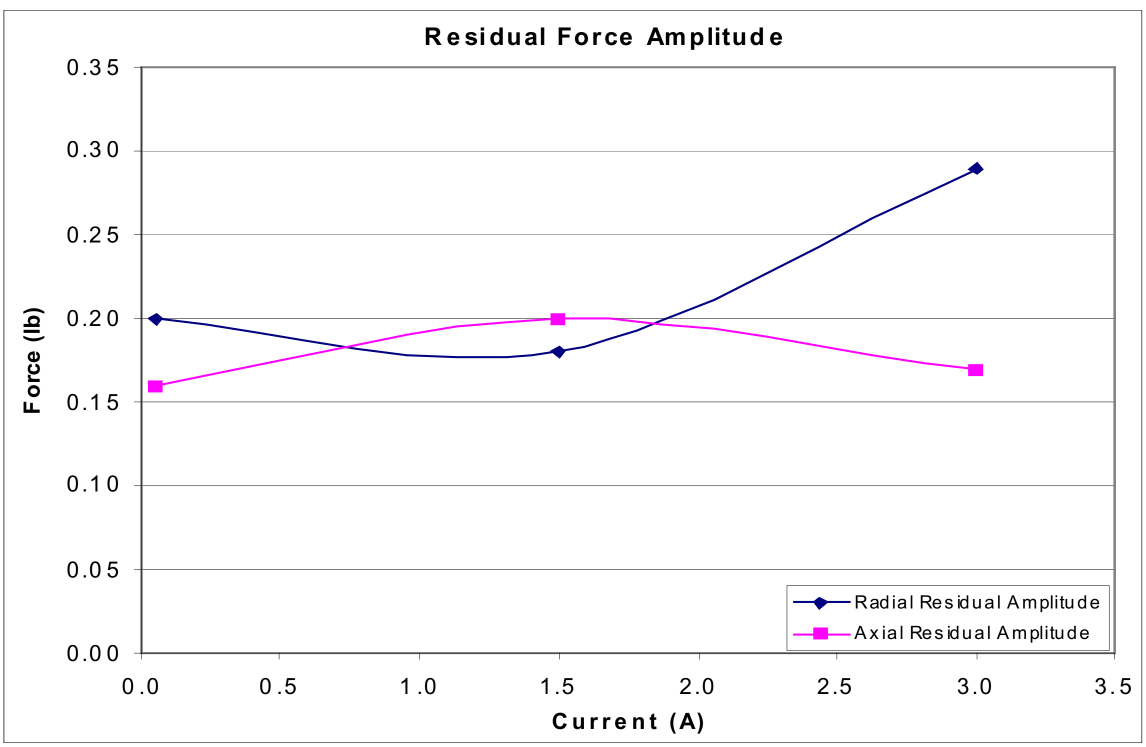

Figure 8 The residual force amplitude varies slightly with current.

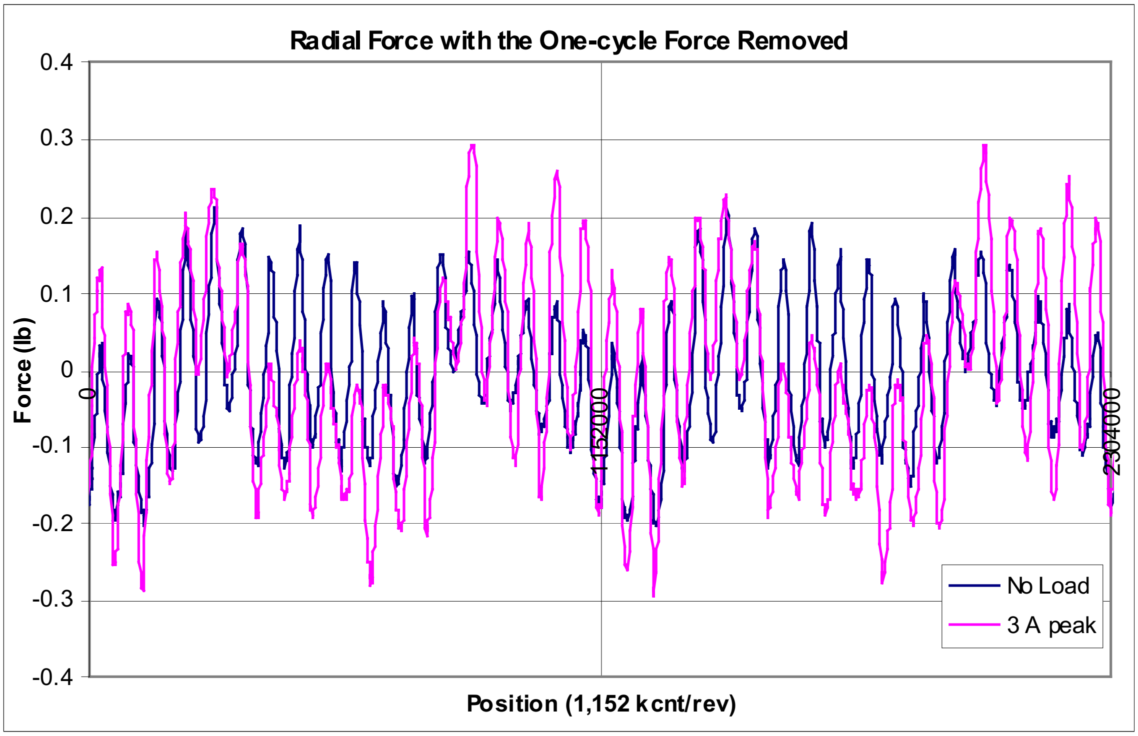

Figure 9 Radial force residual for 0.05 A and 3.0 A with the one-cycle force removed.

Error Motion Estimate for POGAL

The radial force measured for the Aerotech motor will now be applied to the mathematical model of the POGAL B-axis bearing to estimate the effect on radial error motion at the tool point. A turning operation is not sensitive to axial error motion of the B axis so it is ignored. Only static compliance of the hydrostatic bearings is considered in this estimate since the mechanical components are very close coupled. The bearing stiffens significantly with increasing frequency due to squeeze-film damping but this benefit is neglected for the estimate. The POGAL control system will have the ability to sense and reduce any significant error motion for frequencies sufficiently below the position-loop bandwidth.

Radial error motion estimate

The B axis has two opposing bearing surfaces; one is spherical and the other is planar. Radial force is carried solely by the spherical bearing and the resulting radial displacement is measured at the spherical center. The planar bearing carries the moment load that results from the radial force times the distance between the motor and the spherical center. The resulting rotation of the bearing times the distance between the spherical center and the tool point is counter to the radial displacement of the center. Thus with the proper choice of design parameters, the tool-point error motion due to motor force can be eliminated. Table 1 lists the parameters used in the model.

Symbol	*Description*	*Value*	*Unit*
k_r	Radial stiffness of spherical bearing	1.86	lb/µin
k_m	Moment stiffness of planar bearing	60.6	in-lb/µr
a	Tool-point lever arm from spherical center	6.13	inch
b	Motor lever arm from spherical center	-11.0	inch
c_{tp}	Effective sensitivity at tool point	-0.57	µin/lb

Table 1 Parameters used in the B-axis bearing model for estimating radial error motion at the tool point.

Although the 5.2 lb one-cycle radial force does not cause error motion, it is interesting to compute the shift it causes to the axis of rotation. Applying this to the model causes a shift of 3.0 µin (76 nm) at the tool point. The residual radial force does cause error motion and the value measured for the 3 A test, 0.29 lb, is applied to the bearing model to obtain the estimate. The result, 0.17 µin (4.2 nm), is small but on the order of a very good Blockhead™ spindle. Thus some degradation in error motion could be observed but the controller can easily correct it.

Summary

The test results for the Aerotech motor combined with a mathematical model of the POGAL B axis indicate that the additional error motion caused by the motor will be rather small and easily correctable by the controller. The slotless design of the motor integrates the pull of 18 slightly different pole magnets to a nearly constant rotating radial force on the bearing causing primarily shift of the axis of rotation rather than error motion. Axial error motion is not in a sensitive direction for turning. Non symmetries in the magnets and windings cause residual radial and axial forces slightly affected by current, although with no clear trend. The effect on the B axis should not be an issue.